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ROLLING-ELEMENT FATIGUE LIFE OF AUSFORMED M-50 STEEL BALLS

by Richard J. Parker and Erwin V. Zaretsky

Lewis Research Center

Cleveland, Ohio

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ABSTRACT

Rolling-element fatigue lives of a group of ausformed consumable-electrode vacuum melted (CVM) AISI M-50 balls were compared with two groups of conventionally processed CVM AISI M-50 balls in the NASA five-ball fatigue tester. Results indicate an improvement in fatigue life with the ausformed AISI M-50 balls at least three times that of the conventionally processed AISI M-50 balls.

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SUMMARY

The NASA five-ball fatigue tester was used to determine the effect of ausforming 7/16-inch (1.11-cm) diameter consumable-electrode vacuum melted (CVM) AISI M-50 steel balls on rolling-element fatigue life. One group of ausformed balls and two groups of conventionally processed AISI M-50 steel balls were tested at a maximum Hertz stress of 800 000 psi (5.5×10^9 N/m²), a shaft speed of 10 000 rpm; a contact angle of 23° with no heat added. A paraffinic mineral oil was used as the lubricant.

The ausformed balls were fabricated from M-50 bar material which was extruded to a cross-sectional area 20 percent of the original area (80 percent reduction in cross-sectional area) while the material was in a metastable austenitic condition. The 10-percent fatigue life of this group of ausformed balls was three and four times that of two groups of conventionally processed M-50 balls.

INTRODUCTION

High-speed, high-temperature machinery has created unprecedented needs for better design and materials for rolling-element bearings. Coupled with these requirements is the higher ratio of thrust-to-weight in current aircraft turbojet engines. Reliability of these bearings becomes a major consideration because of system complexities. Studies have been undertaken to improve the fatigue characteristics of presently available bearing steels. Results of these studies are seen in improved steel making techniques, better forging techniques, and manufacturing and fabricating processes (ref. 1). Among these processes is one which involves working of steel which is in a metastable austenitic condition. This process is commonly called ausforming.

The process of ausforming was first discussed in reference 2 in which significant improvements in both material strength and ductility were reported. Additional work with the ausforming process was performed and reported in references 3 to 5. The results of this research substantiated the work of reference 2. Subsequent research

(ref. 6) showed that AISI M-50 steel rolling-element bars made by the ausforming process exhibited 10-percent fatigue lives as much as seven times that of bars manufactured from conventionally processed AISI M-50.

The objective of the research reported herein was to experimentally determine whether the ausforming process, as applied to bearing balls, would produce increases in rolling-element fatigue life over conventionally processed bearing balls. Tests were conducted in the five-ball fatigue tester with upper test balls made from ausformed CVM AISI M-50 steel. Test conditions were a calculated maximum Hertz stress of 800 000 psi (5.5×10^9 N/m²) a shaft speed of 10 000 rpm, a contact angle of 23°, and a nominal race temperature of 150° F (340 K) with a paraffinic mineral oil as the lubricant.

The fatigue life of the ausformed balls was compared with the lives of two groups of balls from two separate heats of conventionally processed CVM AISI M-50 material. The three groups of balls were run under identical conditions. All experimental results were obtained with a single batch of lubricant and with lower balls from another single heat of AISI M-50 material.

MATERIAL

Ausforming Process

The ausforming process consists of an isothermal "warm working" operation performed while the material is in a metastable austenitic condition. The austenite is subsequently transformed in either the lower bainite or martensite transformation region of the time-temperature-transformation (TTT) curve. To apply the ausforming method, the steel must have a sluggish transformation behavior in the temperature range where "warm working" is to take place. This is best illustrated by the TTT curves shown in figures 1 and 2. Figure 1 is a TTT curve for SAE 52100 (ref. 6). The phase changes in this steel occur very rapidly upon quenching from the austenite range, and consequently there is not sufficient time, using conventional working methods, to effect any type of deformation in the austenite prior to its transformation. On the other hand, the curve of figure 2 shows the transformation characteristics of AISI M-50 (private communication with Mr. R. T. Morelli, Crucible Steel Company, Pittsburgh, Pa.). This material is ideally suited for ausforming, as it has a region known as the "bay" region where the austenite is isothermally stable. Sufficient time is available to work the material in this condition as illustrated by the arrow.

Ausforming results in a reduction in size and a more uniform distribution of carbide particles compared to conventionally processed AISI M-50 (ref. 6). Thus the smaller more uniformly distributed carbide particles could have accounted for the longer fatigue

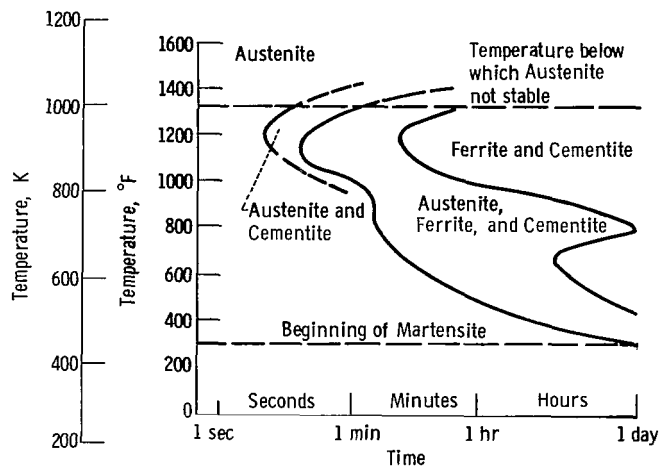


Figure 1. - Time-temperature-transformation curve for SAE 52100. (Absence of "Bay" region makes this material unsuitable for ausforming.) (Ref. 6).

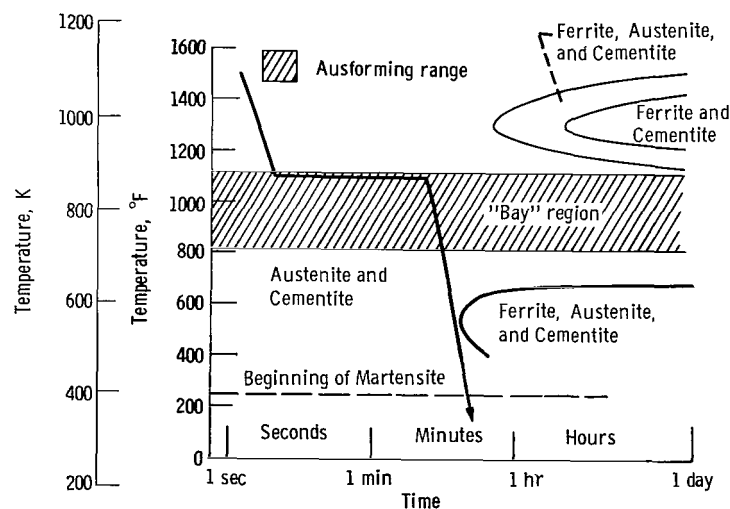


Figure 2. - Time-temperature-transformation curve for AISI M-50 ("Bay" or hold region makes this steel suitable for ausforming. Arrow indicates ausforming cycle.)

life of the bearings made of ausformed material by lessening the severity of dislocation pileups which cause stress concentrations and accelerate crack initiation and propagation. It is believed that the "warm work" imparted to the material during the ausforming process provided more numerous nucleation sites which accounted for the relatively uniform carbide precipitation. The added strain energy also speeded up the time-dependent precipitation process which was apparently completed before cooling to room temperature.

Ball Manufacture

Bearing balls having a diameter of 7/16 inch (1.11 cm) made from ausformed AISI M-50 were used as test specimens. These ausformed balls were manufactured from consumable-electrode vacuum melted (CVM) AISI M-50 bar stock having an initial diameter of $1\frac{3}{8}$ inch (3.49 cm).

The following ausforming and heat treatment process was followed:

- (1) The bar was preheated to 1500⁰ F (1090 K) for 30 minutes.
- (2) It was then austenitized at 2075⁰ to 2100⁰ F (1410 to 1420 K) for 30 minutes.
- (3) The bar was then rapid cooled to 1500⁰ F (1090 K) while still in the inert atmosphere of a specially designed furnace.
- (4) The bar was extruded at 1200⁰ F (920 K) into a 5/8-inch (1.59-cm) diameter bar. This ausforming process provided an 80-percent reduction in cross-sectional area. This 80-percent reduction provided optimum fatigue life for CVM AISI M-50 bearing components fabricated by the ausforming process in reference 6.
- (5) The 5/8-inch (1.59-cm) diameter bar was then tempered for 2 hours at 600⁰ F (590 K).
- (6) A rough ball shape of about 1/2-inch (1.27-cm) diameter was machined using carbide cutting tools.
- (7) The rough balls were tempered twice for 2 hours at 1025⁰ F (825 K).
- (8) The final grind was performed to produce the finished 7/16-inch (1.11-cm) diameter balls. The steps in the ausformed ball processing are shown in figure 3.

The heat treatment specifications used for the balls from reference groups I and II are shown in table I.

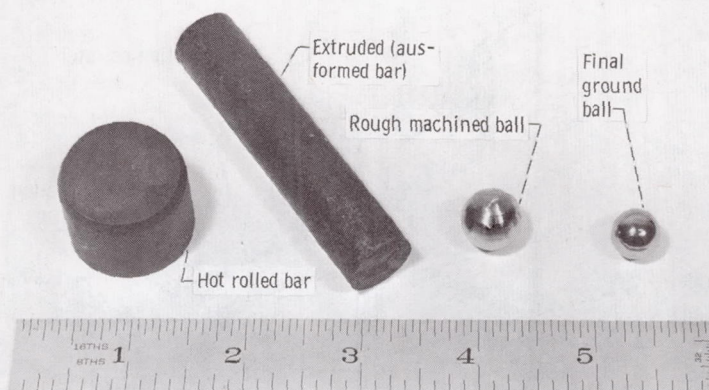


Figure 3. - Processing steps for ausformed AISI M-50 balls.

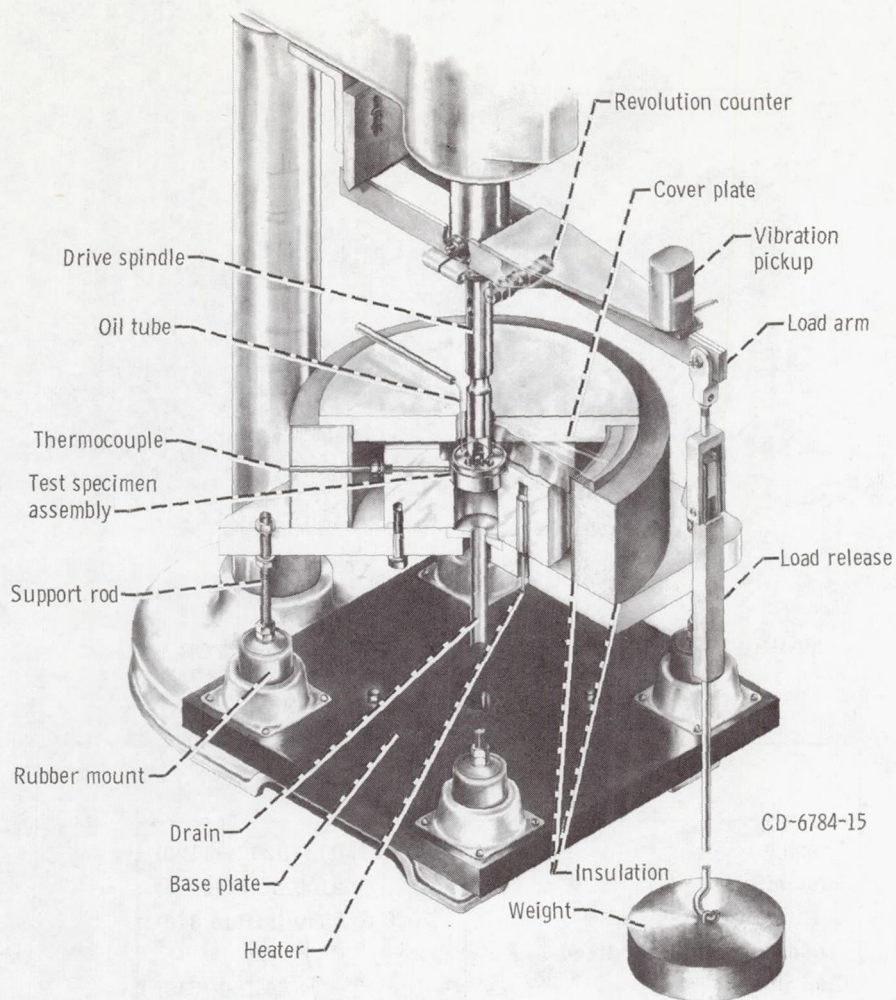
TABLE I. - HEAT TREATMENT SPECIFICATIONS FOR
BALLS FROM REFERENCE GROUPS I AND II

Operation	Temperature, °F (K)
Preheat	1400 to 1550 (1030 to 1120)
Austenitize	2100±10 (1420±5)
Quench in molten salt and hold until equalized	1000 to 1050 (810 to 840)
Cool in air	To 150 (340)
Temper for 2 hours	1025±10 (825±5)
Subzero cooling for 1½ to 2 hours	-110 to -150 (195 to 170)
Temper for 2 hours	1025±10 (825±5)
Temper for 2 hours	975±10 (800±5)

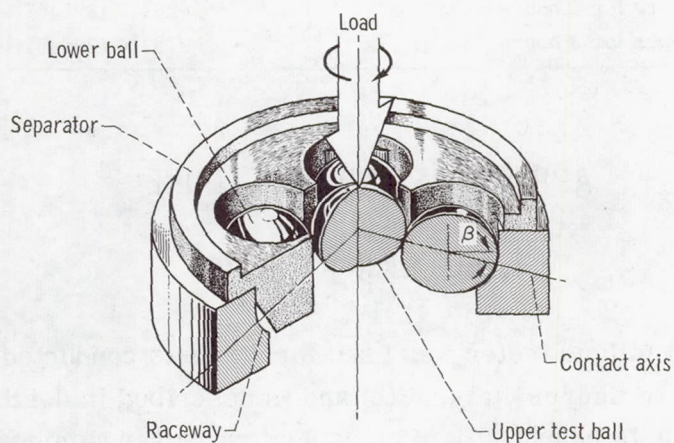
APPARATUS AND PROCEDURE

Five-Ball Fatigue Tester

The NASA five-ball fatigue tester was used for all tests conducted. The apparatus is shown schematically in figures 4(a) and (b) and is described in detail in reference 7. This fatigue tester consists essentially of an upper test ball pyramided on four lower support balls that are positioned by a separator and are free to rotate in an angular-contact raceway. System loading and drive are supplied through a vertical drive shaft. For



(a) Cutaway view of five-ball fatigue tester.



(b) Schematic of five-ball test assembly.

Figure 4. - Test apparatus.

every revolution of the drive shaft, the upper test ball received three stress cycles. The upper test ball and raceway are analogous in operation to the inner and outer races of a bearing, respectively. The separator and the lower balls function in a manner similar to the race and the balls in a bearing.

Fatigue Testing

Before they were assembled in the five-ball fatigue tester, all test-section components were flushed and scrubbed with ethyl alcohol and wiped dry with clean cheesecloth. The specimens were examined for imperfections at a magnification of 15 diameters. After examination, all specimens were coated with test lubricant to prevent corrosion and wear at startup. A new set of lower balls was used with each upper test-ball specimen. When a lower ball failed during the tests, the lower ball set was replaced and the test continued. The speed, outer-race temperature, and oil flow were monitored and recorded at regular intervals. After each test, or when the lower ball set was replaced, the outer race of the five-ball system was examined visually for damage. If any damage was discovered, the race would be replaced prior to further testing.

Fatigue tests were conducted in the five-ball fatigue tester at a maximum Hertz stress of 800 000 psi (5.5×10^9 N/m²), at a drive-shaft speed of 10 000 rpm, and at a contact angle of 23° (indicated by β in fig. 4(b)). The outer-race temperature stabilized at approximately 150° F (340 K) with no heat added. The stress that was developed in the contact area was calculated by using the Hertz formulas given in reference 8.

Method of Presenting Fatigue Results

The total test time for each specimen was recorded and converted to total stress cycles. The statistical methods of reference 9 for analyzing rolling-element fatigue data were used to obtain a plot of the log log of the reciprocal of the probability of survival as a function of the log of stress cycles to failure (Weibull coordinates); For convenience, the ordinate is graduated in statistical percent of specimens failed. From these plots, the number of stress cycles necessary to fail any given portion of the specimen group may be determined. Where high reliability is of paramount importance, the main interest is in early failures. For purposes of comparison, the 10-percent life on the Weibull plot was used. The 10-percent life is the number of stress cycles within which 10-percent of the specimens can be expected to fail; this 10-percent life is equivalent to a 90-percent probability of survival. The failure index indicates the number of specimens that failed out of those tested.

RESULTS AND DISCUSSION

A group of 7/16-inch (1.11-cm) diameter ausformed CVM AISI M-50 steel balls were tested as upper balls in the NASA five-ball fatigue tester. For comparison, two groups of conventionally processed 7/16-inch (1.11-cm) diameter CVM AISI M-50 steel balls were tested at identical conditions. Lower balls were 1/2-inch (1.27-cm) diameter CVM AISI M-50 steel of a separate heat of material. Standard test conditions were ambient temperature (i. e., no heat added), a maximum Hertz stress of 800 000 psi ($5.5 \times 10^9 \text{ N/m}^2$) and a contact angle of 23° . A paraffinic mineral oil was used as the lubricant. The results of the fatigue tests are presented in figure 5 and summarized in table II. At the 10-percent life level, the ausformed balls gave lives approximately four and three times the lives of reference groups I and II, respectively.

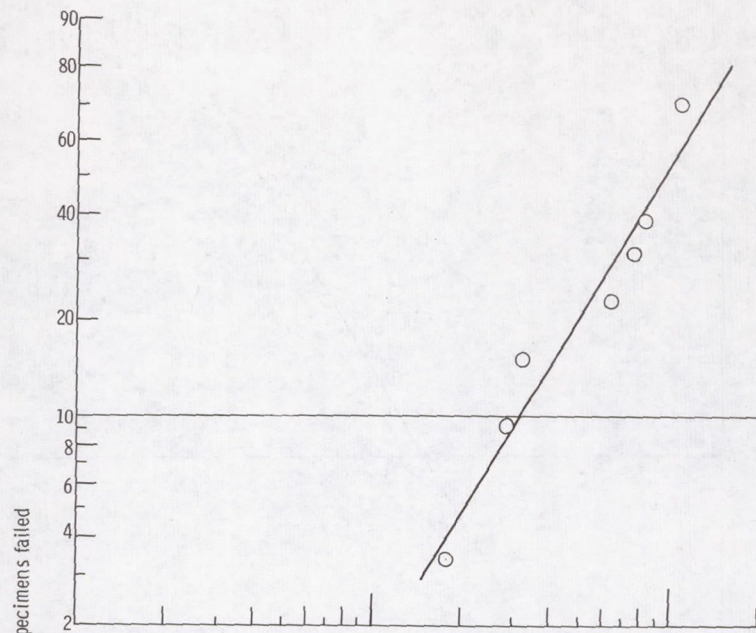
In order to determine the significance of the apparent difference in fatigue lives between the ausformed balls and the conventionally processed balls, confidence numbers were calculated by the methods of reference 9. The confidence numbers listed in table II indicate the percentage of the time that the 10-percent life with a group of AISI M-50 ausformed balls will be greater than that of a group of conventionally processed AISI M-50 balls tested under identical conditions. The confidence number of 90 percent for both reference groups indicates a high degree of significance in these experimental results. Further, a composite confidence number of 94 percent is obtained when comparing both

TABLE II. - FATIGUE LIFE RESULTS WITH AUSFORMED AND
CONVENTIONALLY PROCESSED M-50 STEEL BALLS

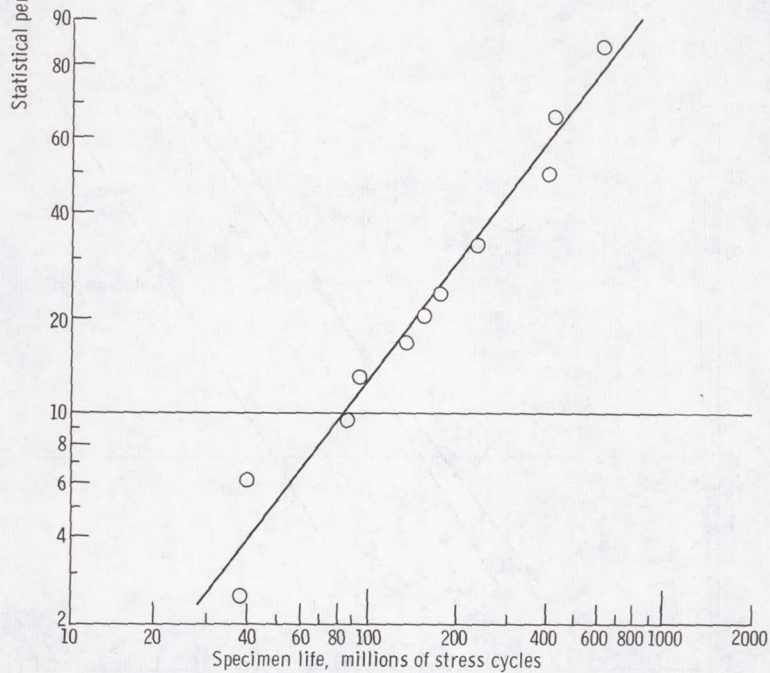
[7/16-in. (1.11-cm) ball diameter; maximum Hertz stress,
800 000 psi ($5.5 \times 10^9 \text{ N/m}^2$); speed, 10 000 rpm; lubri-
cant, paraffinic mineral oil.]

Upper ball	10-percent fatigue life, millions of stress cycles	50-percent fatigue life, millions of stress cycles	Weibull slope	Failure index	Confi- dence number, percent ^a
Ausformed	315	964	1.6	7 out of 22	---
Reference group I	84	345	1.3	11 out of 28	90
Reference group II	101	308	1.7	14 out of 26	90

^aPercentage of time that the 10-percent life with a group of M-50 ausformed balls will be greater than that of a group of conventionally processed M-50 balls.



(a) Ausformed; failure index, 7 out of 22.



(b) Reference group I; failure index, 11 out of 28.

Figure 5. - Rolling-element fatigue life of CVM AISI M-50 steel balls.
Maximum Hertz stress, 800 000 psi (5.5×10^2 N/m²); speed, 10 000 rpm;
outer race temperature, 150° F (340 K); lubricant, paraffinic mineral
oil.

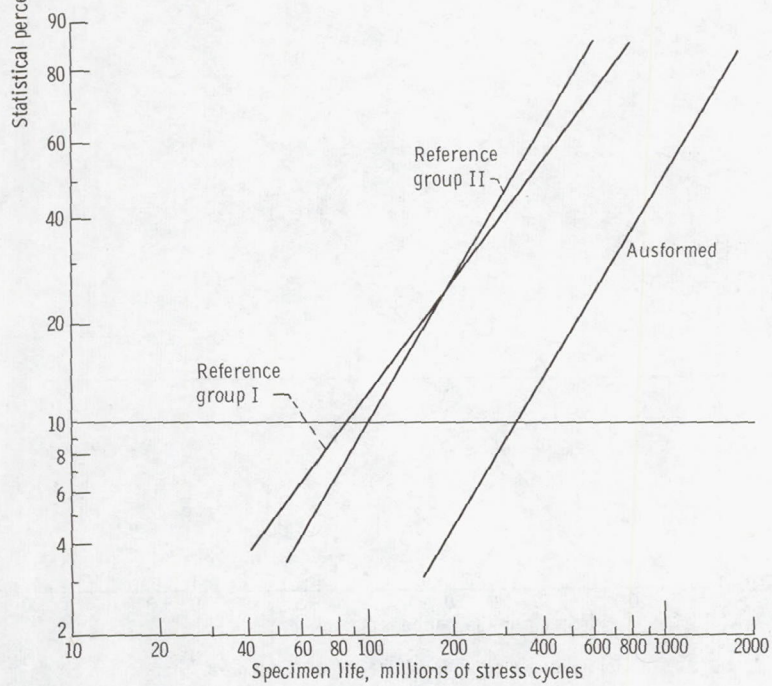
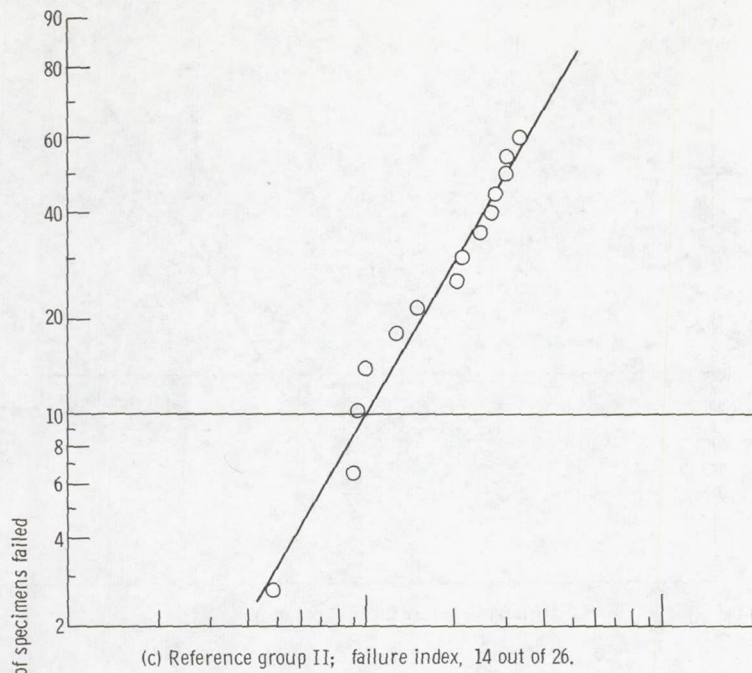


Figure 5. - Concluded.

reference groups with the ausformed balls. This indicates an even greater degree of significance in the results.

It was reported in reference 6 that ausformed CVM AISI M-50 test bars fatigue tested in a rolling-contact (R-C) fatigue tester gave a 10-percent life seven times the life of conventionally processed bar specimens. Additionally, 35-millimeter bore deep-groove ball bearings with ausformed AISI M-50 inner races yielded fatigue lives nine times those of bearings having inner races of conventionally processed AISI M-50 (ref. 10). Although these bearings had ausformed AISI M-50 balls, only inner-race fatigue failures were considered in the analysis. While the ausformed balls in the present research showed improvement over two groups of conventionally processed balls, the effect was not as great as with the R-C fatigue data (ref. 6) or the bearing data (ref. 10). This deviation may be explained on the basis of grain orientation and hardness.

It was reported in reference 11 that grain orientation (fiber flow or grain flow) in bearing materials can affect rolling-element fatigue life. The grain flow pattern resulting from the forging of a conventionally processed ball is shown in figure 6(a). End grain (polar area or equator area, in fig. 6(a)) exposed at a rolling-element surface has

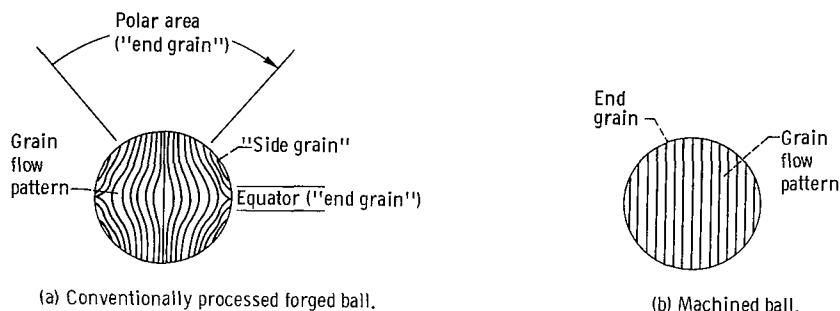


Figure 6. - Representation of grain flow in section of bearing ball.

been determined to be weaker in fatigue than side grain. The ausformed balls, being machined rather than forged, will have a grain pattern resembling parallel, straight lines as shown in figure 6(b). If the ausforming process had no effect on rolling-element fatigue, it would be expected that the life of the ausformed balls would be less than that of the conventionally processed reference balls because of the greater amount of end grain. Since the ausformed balls had lives greater than both groups of reference balls, it is believed that ausforming more than offsets the decrease in fatigue life resulting from undesirable grain flow. The greater lives can be attributed to improved carbide distribution and a more homogenous material structure (ref. 6). Further, it might be

TABLE III. - MEASURED HARDNESS
OF M-50 TEST BALLS AT
ROOM TEMPERATURE

Ball	Hardness, Rockwell C scale
Ausformed	62.3±1.0
Reference group I	64.5±0.5
Reference group II	62.9±0.5
Lower balls	61.5±1.0

possible to achieve an even greater life increase with the ausformed balls by altering the manufacturing process to decrease the amount of end grain.

The hardness of the balls used in these fatigue tests are shown in table III. The hardness of ausformed balls is in the same range as reference group II. The hardness of reference group I balls was between one and two points Rockwell C higher than the ausformed balls. For M-50 material, higher hardness (within this hardness range) will generally give longer fatigue lives (ref. 7). Thus, if the hardness of the ausformed balls and reference group I were the same, an even greater difference in fatigue life between these two groups might be expected. It can be concluded from the results of these tests that the ausforming process can increase rolling-element fatigue life by a factor of at least 3. If effects of end grain and hardness are considered, this factor may conceivably be as high as 7 to 9 as reported in references 6 and 10.

SUMMARY OF RESULTS

The NASA five-ball fatigue tester was used to determine the effect of ausforming 7/16-inch (1.11-cm) diameter consumable-electrode vacuum melted (CVM) AISI M-50 steel balls on rolling-element fatigue life. Tests were conducted with ausformed balls and two groups of conventionally processed CVM AISI M-50 balls at a maximum Hertz stress of 800 000 psi (5.5×10^9 N/m²), with no heat added. Lower balls were conventionally processed CVM AISI M-50 balls of 1/2-inch (1.27-cm) diameter. A paraffinic mineral oil was used as the lubricant. The results of the fatigue tests indicate that the aus-

formed AISI M-50 balls have a fatigue life at least three times that of conventionally processed AISI M-50 balls.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, September 25, 1968,
126-15-02-28-22.

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